

Inferring the mass of sub-millimetre galaxies by exploiting their gravitational magnification of background galaxies

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ABSTRACT

Dust emission at sub-millimetre wavelengths allows us to trace the early phases of star formation in the Universe. In order to understand the physical processes involved in this mode of star formation, it is essential to gain knowledge about the dark matter structures – most importantly their masses – that sub-millimetre galaxies live in. Here we use the magnification effect of gravitational lensing to determine the average mass and dust content of sub-millimetre galaxies with $250\ \mu\text{m}$ flux densities of $S_{250} > 15\ \text{mJy}$ selected using data from the Herschel Multi-tiered Extragalactic Survey. The positions of hundreds of sub-millimetre foreground lenses are cross-correlated with the positions of background Lyman-break galaxies at $z \sim 3 - 5$ selected using optical data from the Canada-France Hawaii Telescope Legacy Survey. We detect a cross-correlation signal at the $7\text{-}\sigma$ level over a sky area of one square degree, with $\sim 80\%$ of this signal being due to magnification, whereas the remaining $\sim 20\%$ comes from dust extinction. Adopting some simple assumptions for the dark matter and dust profiles and the redshift distribution enables us to estimate the average mass of the halos hosting the sub-millimetre galaxies to be $\log_{10} [M_{200}/M_{\odot}] = 13.17^{+0.05}_{-0.08}(\text{stat.})$ and their average dust mass fraction (at radii of $> 10\ \text{kpc}$) to be $M_{\text{dust}}/M_{200} \approx 6 \times 10^{-5}$. This supports the picture that sub-millimetre galaxies are dusty, forming stars at a high rate, reside in massive group-sized halos, and are a crucial phase in the assembly and evolution of structure in the Universe.

Key words: Submillimeter: galaxies, Gravitational lensing: weak, Galaxies: high-redshift

1 INTRODUCTION

In the current picture galaxies form in the centres of the gravitational potential wells of dark matter halos, when gas cools and star formation sets in (Eggen et al. 1962). However, many of the observed properties of galaxies – e.g., scaling laws between different observables like the Faber & Jackson (1976) relation, the Tully & Fisher (1977) relation, and the $m\text{-}\sigma$ relation (Ferrarese & Merritt 2000) – remain to be explained by a complete theory of galaxy formation and evolution. We know from observations in the $z < 1$ Universe that star formation efficiency, i.e., the fraction of baryonic mass turned into stars, depends on the environment, most importantly on the mass of the dark matter halo as shown by Leauthaud et al. (2012). The bulk of star formation, however, happened at earlier cosmic epochs (Madau et al. 1996), when the Universe was less than half of its current age, which necessitates studies at high redshift ($z \gtrsim 1$).

Young stars are still enveloped in clouds of gas and dust, and therefore most of their radiation is absorbed by dust, and re-emitted at far-infrared wavelengths. Since this is the dominant source of emission at these wavelengths, the luminosity of a galaxy in the far-infrared wavelength range is directly related to the amount of young stars, and therefore the rate of star formation. Sub-millimetre telescopes are sensitive to this radiation. Moreover, the detection of this light is less sensitive to redshift than in the optical, due to the fortunate shape of the spectral energy distributions of galaxies in the sub-millimetre regime yielding samples of star-forming galaxies over a wide redshift range. Establishing a picture of the dark matter environment of these sub-millimetre galaxies through measuring their total (i.e., baryonic plus dark matter) masses is hence a fundamental ingredient for understanding the build-up of stellar mass over cosmic time.

Gravitational lensing is the most direct method of measuring mass in the distant Universe, irrespective of whether

it consists of dark or baryonic matter, and independent of any assumptions about its dynamical state. Thus, it represents a powerful tool for measuring the masses of dark matter structures, both using fewer astrophysical assumptions and being complementary to, e.g., velocity dispersion measurements. In many cases the lensing effect of an individual deflector is too weak to be detected. In weak gravitational lensing (WL; see e.g. Bartelmann & Schneider 2001) a statistical approach is used, averaging the signals of many lenses and/or sources.

In order to detect the effects of WL by a lens population, a suitable source population is needed that lies behind the lenses (from the observer’s point of view). The extended redshift distribution of sub-millimetre galaxies means that most potential background galaxies are spatially unresolved in even the best ground-based optical data. Hence the traditional shear technique of WL, which requires ellipticity estimates, cannot be used in this particular case, and one has to turn to the magnification technique, which does not require resolved sources (Van Waerbeke et al. 2010).

Here we measure the WL-magnification effect of a sub-millimetre galaxy sample to estimate their average dark matter halo density profiles. As background sources we use optically-selected Lyman-break galaxies (LBGs; Steidel et al. 1996) which are located at even higher redshifts. The sub-millimetre as well as the optical data are described in Sect. 2. An outline of the magnification technique is given in Sect. 3. Results are presented in Sect. 5 and discussed in Sect. 6. A summary and an outlook are given in Sect. 7. We assume a WMAP7 cosmology throughout (Komatsu et al. 2011): $(\Omega_{\text{M}}, \Omega_{\Lambda}, h, \sigma_8) = (0.27, 0.73, 0.70, 0.81)$.

2 DATA

2.1 Sub-millimetre data

The sub-millimetre galaxies are selected from the Herschel Multi-tiered Extragalactic Survey (HerMES; Oliver et al. 2010; HerMES Collaboration et al. 2012), observed with the Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) on board the *Herschel Space Observatory* in the Cosmic Evolution Survey (COSMOS; Scoville et al. 2007) field. The catalogue¹ was constructed by the HerMES team, using blind extraction at 250 μm and a prior-based extraction for the other two wave bands at 350 μm and 500 μm . Details can be found in Roseboom et al. (2010). Note that these sub-millimetre galaxies constitute the lenses here and not the sources as in Wang et al. (2011).

Unlike 'classical' sub-millimetre sources detected at longer wavelength like, e.g., SCUBA-type (Holland et al. 1999) galaxies, the galaxies detected by SPIRE at 250 μm do not show a strong negative k -correction (Franceschini et al. 1991; Blain & Longair 1993). Hence their redshift distribution does not extend to as high redshifts, which is beneficial for the magnification measurement presented here, since it allows for easier separation between the sub-millimetre lenses and the LBG sources in redshift.

The beam size of Herschel at 250 μm is $\text{FWHM} \approx 18''$. The centroids of the sub-millimetre galaxies in each sky coordinate are known to $\Delta\alpha = \Delta\delta = 0.6 \text{ FWHM}/\text{SNR}$, where SNR is the signal-to-noise ratio of the detection (Iverson et al. 2007). The mean SNR of our lenses is $\overline{\text{SNR}} = 5.3$, which corresponds to centroid errors of $\Delta\alpha = \Delta\delta = 2''$. Additionally, the pointing accuracy of Herschel is limited to $\approx 2''$ as well (Pilbratt et al. 2010). We add these two contributions to the centroid error in quadrature and account for this angular uncertainty in the modelling (see Sect. 4).

2.2 Optical data

The central part of the COSMOS field (1 deg²) was targeted with the MegaCam imager on the Canada France Hawaii Telescope (CFHT) as part of the CFHT Legacy Survey. Very deep images (5- σ limiting magnitudes for point sources of 26.5–28.0) in the *ugriz*-bands from the CARS project (Erben et al. 2009; Hildebrandt et al. 2009a) were used to select a sample of $\sim 17\,500$ Lyman-break galaxies (Hildebrandt et al. 2009a,b) at redshifts $z \sim 3 - 5$. These are too distant to be resolved in the optical data, but they constitute an ideal sample for magnification measurements.

This set of LBGs has been studied in detail in the literature. Their clustering properties are described in Hildebrandt et al. (2009a) and a measurement of the LBG luminosity function based on this data set is presented in van der Burg et al. (2010). Furthermore, these LBGs were already used as background sources for a magnification measurement in a previous study (Hildebrandt et al. 2009b), but then using normal galaxies selected by photometric redshifts as lenses.

¹ available at the HeDaM on-line data base: <http://hedam.oamp.fr/HerMES/>

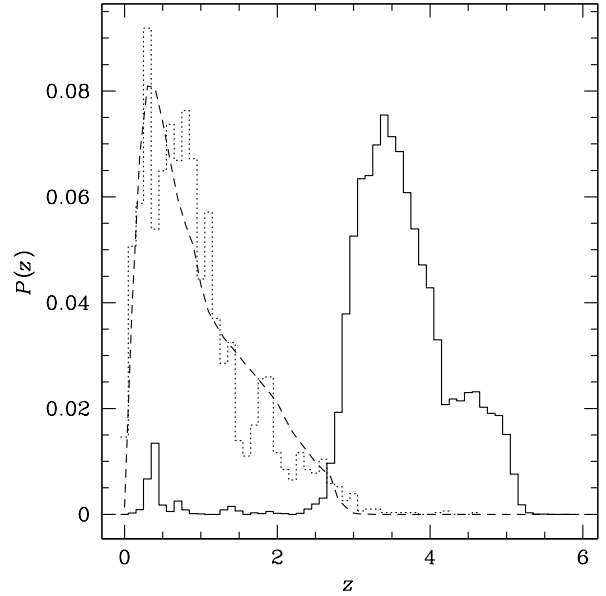


Figure 1. Redshift distributions of the sub-millimetre lenses (dashed: simulation; dotted: photometric redshifts) and the LBG sources (solid) used in the magnification measurement. The separation in redshift is not perfect and therefore we model the contribution from physical clustering (due to redshift overlap) to the cross-correlation signal.

2.3 Redshift distributions

The HerMES catalogue contains 3402 objects in the common area of the optical and sub-millimetre data. For the mass measurement we only consider lenses with a sub-millimetre flux density at 250 μm of $S_{250} > 15 \text{ mJy}$. This is necessary because confusion (and other effects) is more severe at fainter flux densities in the Herschel data, which would make the estimation of a redshift distribution for the lenses very problematic. This redshift distribution is needed to interpret the signal, since it depends on the lens-source geometry, and to estimate a mass. We further apply a colour cut on the sub-millimetre lenses to enhance the separation in redshift. We require the ratio of the flux densities at 500 μm and 250 μm to be $S_{500}/S_{250} < 0.5$. This leaves us with 587 lenses. The measured and simulated redshift distributions of the lenses are presented in Béthermin et al. (2011, 2012b). We use the simulated one in the following. The model of the redshift distribution of the sources is taken from Hildebrandt et al. (2009a). These distributions are plotted in Fig. 1, showing only marginal overlap.

3 TECHNIQUE

The measurement described here is technically similar to the previous measurement by Wang et al. (2011) using sub-millimetre galaxies and magnification, but conceptually it is very different because here we are studying the effects of lensing *by* sub-millimetre galaxies rather than the effects of lensing *by* other sources *on* sub-millimetre galaxies (see also Blake et al. 2006, for a related cross-correlation measurement). Thus, we can study how their dark matter ha-

los deflect light and estimate their average mass through this effect, which was not possible when the sub-millimetre galaxies were used as sources.

As detailed in other studies (Van Waerbeke et al. 2010; Hildebrandt et al. 2011) magnification is a particularly useful tool for measuring the average masses of objects at high redshifts because – unlike shear-based weak lensing methods – it does not require the background sources to be resolved. A large fraction of the sub-millimetre galaxies studied here have redshifts $z > 1$. With the best optical ground-based data there are very few objects at such high redshifts that could be resolved and used as background sources for shear measurements because of the seeing-limited size of the optical point-spread-function (PSF). Even with optical imaging data from the Hubble Space Telescope it becomes increasingly difficult to resolve objects with $z \gtrsim 1.5$ due to PSF size. Thus, the population of sub-millimetre galaxies studied here represents an ideal lens sample for magnification when LBGs are used as background sources.

The WL-magnification effect of the lenses increases the fluxes of background objects and shifts their positions on the sky. This induces a change in their number density, which leads to angular correlations in the positions of lenses and sources on the sky, even in the absence of physical clustering, i.e., when both populations are well separated in redshift (Scranton et al. 2005; Hildebrandt et al. 2009b). Depending on the slope of the magnitude number counts of the source sample, $\alpha = 2.5 \, d \log [N(m)]/dm$, a positive or a negative cross-correlation is expected from WL theory. Bright galaxies with typically steep slopes ($\alpha - 1 > 0$) should show positive correlations, and faint galaxies, with shallow slopes ($\alpha - 1 < 0$), should show anti-correlations.

WL magnification is not the only effect that can cross-correlate the sky position of objects that are far apart along the line of sight. Extinction by dust in the foreground objects can also lead to a characteristic depletion of the number density of background objects, and this has to be included in the modelling to correctly interpret the cross-correlation signal. This behaviour can be described by an effective slope α_{eff} as detailed below.

For this kind of measurement it is particularly important to minimise the overlap in redshift between the lens and source populations to suppress a systematic bias due to physical cross-correlations, which can be much larger than the magnification/extinction signal.

The cross-correlation functions are estimated using the estimator from Landy & Szalay (1993) based on pair counts:

$$w(\theta) = \frac{D_1 D_2 - D_1 R - D_2 R}{RR} + 1, \quad (1)$$

with $D_1 D_2$ being the number of sub-millimetre-LBG pairs in the angular range $[\theta, \theta + \delta\theta]$ normalised by the product of their total numbers, $D_i R$ being the normalised number of pairs between the sub-millimetre/LBG catalogue and a random catalogue (with the same surface geometry) in that angular range, and RR being the normalised number of pairs in the random catalogue in that angular range. By choosing a random catalogue that is much larger than the data catalogues the shot noise introduced by the random catalogue is suppressed.

It has been shown in Ménard et al. (2003) and Scranton et al. (2005) that the signal-to-noise ratio of a magnification

measurement can be boosted when every background galaxy is given a weight that corresponds to the $\alpha - 1$ value at its magnitude. The same can be done if there is additional dust extinction by instead using an effective weight, $\alpha_{\text{eff}} - 1$.

For the optimally-weighted correlation function the same estimator is used, but $D_1 D_2$ and $D_2 R$ are replaced by the sums of weights instead of the number of pairs (Hildebrandt et al. 2009b). The weights are $\alpha_{\text{eff}} - 1$ (see Sect. 5 for a definition) for the LBG in each pair accounting for the fact that part of the signal is due to extinction. Such a weighting maximises the signal-to-noise ratio of the magnification/extinction measurement (Ménard et al. 2003; Scranton et al. 2005). The gain is considerable for cases where the weight changes appreciably over the whole range of magnitudes of the background sample (typically for very deep data as used here; see also Fig. 2).

4 THEORETICAL BACKGROUND

We assume that the halos hosting the sub-millimetre galaxies can be described by a single NFW (Navarro et al. 1996) halo. This model has two parameters, the mass M_{200} and the concentration c . Detailed dark matter N-body simulations show that these two parameters are strongly correlated and a relation can be established between the two. Here, we use the relation by Prada et al. (2012) to reduce the number of parameters in our mass model. The magnification profile of an NFW halo is described in Wright & Brainerd (2000).

We model the signal of the optimally-weighted cross-correlation function in the following way:

$$w_{\text{opt}}(\theta) = w_{\mu}(\theta) + w_{\tau}(\theta) + w_{\text{cc}}(\theta), \quad (2)$$

where w_{μ} describes the contribution from magnification, w_{τ} describes the contribution from dust extinction in the lens galaxies, and w_{cc} is the physical clustering part of the signal that is due to redshift overlap between lenses and sources and should be minimised.

The magnification signal can be calculated from lensing theory:

$$w_{\mu}(\theta) = \int_{m_{\text{min}}}^{m_{\text{max}}} [\alpha_{\text{eff}}(m) - 1] [\mu(\theta)^{\alpha(m)-1} - 1] \hat{N}(m) dm, \quad (3)$$

with $m_{\text{min/max}}$ being the faintest and brightest magnitudes of the background sample, $\alpha_{\text{eff}}(m) - 1$ being the effective weight, $\mu(\theta)$ being the magnification profile of an NFW halo,² $\alpha(m) - 1 = 2.5 \, d \log [N(m)]/dm - 1$ being the weight in absence of extinction (taken from the LBG luminosity function of van der Burg et al. 2010), and $\hat{N}(m)$ being the normalised number counts of the LBGs.

The dust absorption A is related to the optical depth through

$$A = 2.5/\ln(10) \, \tau = 1.08\tau. \quad (4)$$

We assume that A and the magnification excess $\delta\mu = \mu - 1$

² For readability we do not include the redshift dependence here. But it should be clear that $\mu(\theta)$ has to be calculated by integrating over the redshift distributions of the lenses and sources.

are related by³

$$A = c_d \delta\mu. \quad (5)$$

Here we assume that this is true on average. The redshift dependence of the dust extinction and the magnification is certainly different. Hence halos at different redshift will contribute differently to the magnification and extinction signals. We neglect this effect in the following but note that firm conclusions on the shape of the dust profile can only be drawn if such effects are included in the modelling. The mass estimate is not directly affected by this simplification. Under these assumptions the dust signal becomes:

$$w_\tau(\theta) = \int_{m_{\min}}^{m_{\max}} [\alpha_{\text{eff}}(m) - 1] \times [1.08 c_d 10^{-0.4\alpha(m)} \delta\mu(\theta) - 1] \hat{N}(m) dm. \quad (6)$$

The contribution from physical clustering to the angular correlation function are modelled by

$$w_{\text{cc}}(\theta) = \int_{m_{\min}}^{m_{\max}} [\alpha_{\text{eff}}(m) - 1] b_1 b_2 w_{\text{DM}}(\theta) \hat{N}(m) dm, \quad (7)$$

where $b_{1/2}$ are the average bias factors of the lenses and sources, respectively, and w_{DM} is the angular correlation function of the dark matter field⁴. We conservatively estimate $b_1 = b_2 = 2$ in our analysis.

5 RESULTS

The angular cross-correlation (unweighted) between the positions of all sub-millimetre lenses in the 1 deg^2 area (3402 objects; no flux cut) and the LBG sources in different magnitude slices at close separations is shown in Fig. 2. Here we use one broad angular bin with $1''.8 < \theta < 6''.0$. As expected, the positions of the brighter background galaxies are positively correlated with the positions of the lenses, while the positions of the fainter ones are anti-correlated. However, the dashed line, which shows the expected amplitude from magnification only, without dust extinction, does not fit the data points. The solid line represents the expected amplitude of the cross-correlation function assuming that on average the dust absorption is proportional to the magnification excess (note that this is well supported by results from Ménard et al. 2010, using SDSS data). We fit for the dust normalisation constant c_d , obtaining a best-fit value of $c_d = 0.35$. The overall normalisation was left as another free parameter and both predictions were multiplied by this value. In both cases we model $N(m)$ from the LBG luminosity function estimates by van der Burg et al. (2010).

Ménard et al. (2010) found a value of $c_d \approx 0.1$ using a magnitude-limited, optically-selected, low- z galaxy sample from the Sloan Digital Sky Survey. Thus, the sub-millimetre galaxies we study here are – not surprisingly – considerably

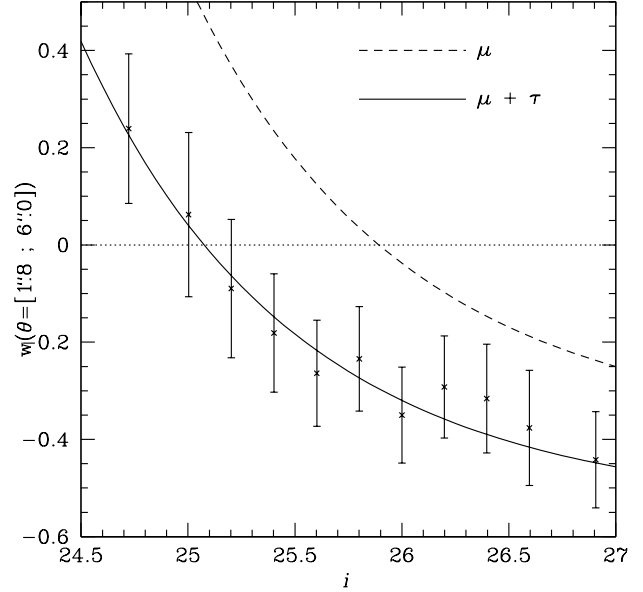


Figure 2. Amplitude of the angular cross-correlation function between 3402 sub-millimetre lenses and LBG sources as a function of the LBG i -band magnitude in the angular interval $1''.8 < \theta < 6''.0$. Errors are Poissonian. The dashed line represents the expected amplitude if there was only magnification. The solid line represents a more realistic model including the effects of extinction by dust in the lenses.

more dusty (although the c_d values cannot be compared directly because of the different rest frame wavelengths of the filters used for the selection of the lenses).

Physical clustering signals due to redshift overlap between lenses and sources are always positive. Thus, detecting a negative cross-correlation, as shown in Fig. 2, already suggests that we do not have significant redshift overlap here.

Here, we use all 3402 lenses detected in the sub-millimetre data to improve the statistics and be able to constrain the scaling between magnification and extinction. However, we limit the following analysis to the 587 objects with $S_{250} > 15 \text{ mJy}$ and $S_{500}/S_{250} < 0.5$, for which we can estimate a reliable redshift distribution (see Sect. 2.3). By applying the c_d value found from the whole sample of 3402 objects to the high-confidence sample of 587 objects we implicitly assume that the redshift distribution, as well as the scaling between $\delta\mu$ and A , does not differ significantly between the two samples. With the current data and models this cannot be tested directly and has to remain an assumption here.

In Fig. 3 the optimally-weighted cross-correlation function between these 587 sub-millimetre galaxies and the full set of background LBGs is shown, with errors estimated from a jack-knife resampling of the background sample. We detect a signal at the $7\text{-}\sigma$ level. The best-fit value for $c_d (= 0.35)$ that we take from the previous measurement indicates that the majority of this signal is due to magnification and not extinction. Note that the accurate relative contributions depend on the absolute value of the magnification itself (and hence also on angular scale). At small angular scales mag-

³ Note that this does not constrain the dust profile yet because c_d can be a function of angular scale.

⁴ This is calculated with the equation from Limber (1953). We used the code by Hamana et al. (2004) for this. The contribution from physical clustering has to be weighed appropriately with the product of the redshift distributions of lenses and sources.

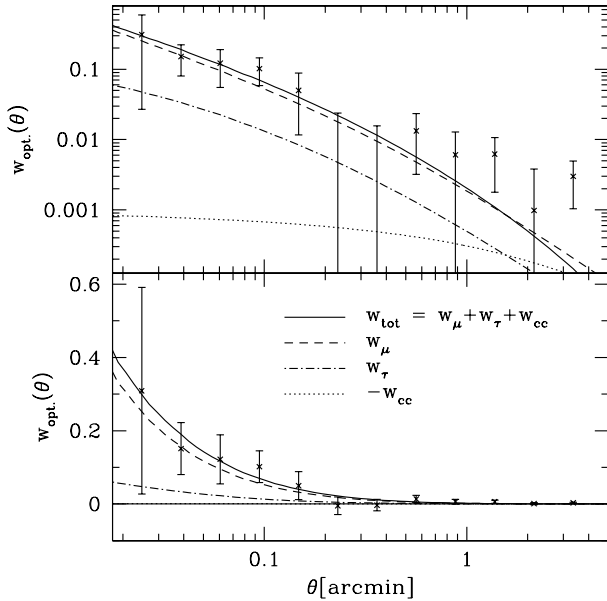


Figure 3. Optimally-weighted angular correlation function between 587 sub-millimetre galaxies with $250\,\mu\text{m}$ flux density $S_{250} > 15\text{ mJy}$ and all background LBGs. The weights are based on the results presented in Fig. 2 with only the brightest Lyman-break galaxies getting a positive weight and the fainter ones all getting a negative weight. The solid line represents the best-fit model, consisting of contributions from magnification (dashed line), dust extinction (dot-dashed), and a negative contribution from physical clustering between lenses and sources (dotted, and almost negligible). The top panel shows a logarithmic scale for the correlation amplitude whereas the bottom panel has a linear scale. Errors are estimated from a jack-knife resampling of the background population.

nification contributes about 85% to the signal, whereas at large angular scales its contribution drops to about 75%.

We fit the model from Eq. 2 to the data, which represents the magnification of an NFW dark matter halo, as well as the extinction of a dust halo whose dust is distributed according to the same profile. Additionally we take the small contribution from physical cross-correlations w_{cc} into account, which is further suppressed because of the weighting scheme. Due to the fact that most of the background LBGs have negative weights, $\alpha_{\text{eff}} - 1$, w_{cc} actually becomes negative in this optimally-weighted case.⁵ We also account for errors in the centroid positions of the sub-millimetre lenses due to the limited resolution of Herschel.

The best-fit estimate of the average NFW halo mass within r_{200} is $\log_{10} [M_{200}/M_{\odot}] = 13.17^{+0.05}_{-0.08}(\text{stat.})$ or $M_{200} = 1.48^{+0.18}_{-0.25}(\text{stat.}) \times 10^{13} M_{\odot}$, directly confirming that sub-millimetre galaxies are hosted by very massive halos.

Note that by assuming that dust follows mass (see above) we can exploit the contribution from extinction to the signal in order to actually constrain the mass. The quoted error contains contributions from shot-noise as well as from clustering of the background population. No uncertainties

⁵ This also means that not accounting for or underestimating w_{cc} would lead to an underestimate of the mass.

originating from the measurement of c_d , the assumption that dust follows mass, the assumed redshift distributions, or the physical clustering model are included here, because these uncertainties are very hard to quantify at the current stage, but could well be substantial.

Our best-fit model also suggests that sub-millimetre galaxies are very dusty. Assuming that the extinction law of the dust in these galaxies is similar to that found in the Small Magellanic Cloud (Ménard et al. 2010), the dust mass fraction at the scales we are probing ($\gtrsim 10\text{ kpc}$) can be estimated to be roughly $M_{\text{dust}}/M_{200} \approx 6 \times 10^{-5}$.

6 DISCUSSION

6.1 Details of the modelling

The magnification exceeds $\mu = 1.5$ for the smallest scales that we are probing here, taking into account that the dust extinction contributes 15% of this signal. Thus, this is not strictly weak lensing but rather an intermediate regime between strong and weak lensing where a statistical technique – similar to what is used in weak lensing – is applied. Note that because of this we do not assume the weak lensing limit (i.e. $\delta\mu \ll 1$) in any part of the modelling.

Both, the magnification as well as the extinction, lead to a net depletion of background sources behind the sub-millimetre lenses, hence the negative average weight. Even without directly using colour information, we can still disentangle the two effects because we have a measurement of the average intrinsic luminosity function of the LBGs (van der Burg et al. 2010). Attributing the amplitude of the correlation function solely to either magnification or extinction would lead to inconsistencies as it is shown in Fig. 2.

6.2 Relation to Clustering

Clustering measurements have been used to constrain the dark matter halo masses of sub-millimetre galaxies by interpreting their auto-correlation function in the framework of the halo model (Farrah et al. 2006; Cooray et al. 2010; Amblard et al. 2011; Hickox et al. 2012; Viero et al. 2012). While we also measure a correlation function here, the origin of the signal is very different. The lensing magnification method described here differs in some important aspects from such clustering measurements.

We actually try to suppress the physical clustering contribution to the cross-correlation function as much as possible by separating the sub-millimetre lenses and LBG sources in redshift. The auto-correlation signal that is used by physical clustering measurements represents a systematic nuisance in magnification studies. We model its small contribution to the cross-correlation function here and account for it in the mass measurement, but it is important to note that it is not used to estimate the mass.

In order to interpret an auto-correlation signal from physical clustering, some model for the galaxy bias has to be assumed. No such model is needed to interpret our lensing correlation function on small scales, under the assumption that all sub-millimetre galaxies are central galaxies to their halos.

Another important difference between physical clustering measurements and lensing magnification is the different sensitivity to the shape of the redshift distribution. While the interpretation of the physical angular cross-correlation function depends critically on the width of the redshift distribution, lensing is fairly insensitive to this width because the lensing efficiency is a slowly changing function of redshift. It is mainly the mean redshift that is important here. However, this is only true as long as there is no redshift overlap between lenses and sources. Once there are physical cross-correlations contributing to the signal, as in the measurement presented here, the width becomes important again for estimating this contribution.

6.3 Comparison to abundance matching

We also roughly estimate the mass of halos hosting the sub-millimetre galaxies from abundance matching (Béthermin et al. 2012a) using the following method. We compute the infrared luminosity of a source having the mean redshift and the mean flux of the Herschel sample. We convert this luminosity into star formation rate using the Kennicutt (1998) constant ($1 \times 10^{-10} M_{\odot}/\text{yr}/L_{\odot}$). We finally use the abundance matching results at this SFR and this mean redshift, using an interpolation between the two closest redshifts where the abundance matching was performed. This yields a mass estimate of $\log_{10} [M_{200}/M_{\odot}] = 13.2 \pm 0.2$, in very good agreement with our magnification/extinction measurement.⁶

6.4 Notes on the sub-millimetre catalogue

This sub-millimetre galaxy lens sample represents a fairly faint population. Thus, the number of lenses that are lensed themselves is also very low. A completely negligible fraction of the signal shown in Fig. 3 is due to lensing of both, the lenses and the sources, by foreground structures in front of both (Heavens & Joachimi 2011).

When we use the full catalogue of 3402 objects for the determination of the constant c_d it is very probable that there are a large number of spurious objects in this sample. Note that this does not matter in that particular case because we are only interested in the relative amounts of magnification and extinction there. A spurious source should not add to either of the two and hence not change the result. For the actual mass measurement we use only galaxies with $250 \mu\text{m}$ flux densities of $S_{250} > 15 \text{ mJy}$ as lenses. Given the depth of the data this sample should not contain any spurious sources.

6.5 Limitations and possible extensions

There are several aspects that limit the accuracy of the measurement presented here. We have to use a redshift distribution based on a model for the sub-millimetre lenses to predict the magnification signal. Individual (photometric) redshifts for all sub-millimetre galaxies would certainly help

to overcome any uncertainties in the modelling of their redshift distribution (Béthermin et al. 2012b).

The amount of physical cross-correlation, described by w_{cc} , depends on the redshift distribution of the LBGs, which is taken from simulations (Hildebrandt et al. 2009a). It should be noted that the choice here is actually quite pessimistic. With different plausible choices presented in Hildebrandt et al. (2009a), which are based on modified simulations, the overlap and hence amplitude of w_{cc} would decrease even further. The mass estimate is virtually unaffected by this very small change. We would like to stress that the optimal weighting of the correlation function greatly suppresses the physical cross-correlation. In order to boost the signal-to-noise ratio of the desired signal components each background galaxy is weighted with its expected responsiveness to the combined effects of magnification and extinction. These weights are estimated from the background galaxies' magnitudes. However, the scaling of the physical cross-correlation signal with magnitude of the background galaxies is completely different. This suppression is reflected in the very low amplitude of w_{cc} compared to w_{μ} and w_{τ} in Fig. 3.

We assume that the optical depth of dust extinction in the lenses, τ , follows the magnification excess, $\delta\mu$, such that $\frac{2.5}{\ln(10)}\tau = c_d\delta\mu$. This is motivated by the measurement by Ménard et al. (2010) with low- z galaxies but has not been shown to be true for sub-millimetre galaxies. We can only constrain the value of c_d at small scales where the signal-to-noise ratio is large enough to split up the LBG background sample into several magnitude bins: hence, the choice of the broad angular bin with $1''.8 < \theta < 6''.0$ in Fig. 2. However, our measurement over 1 deg^2 is not powerful enough to fully constrain the angular dependence of the extinction. Future measurements over larger areas could exploit the reddening effect (Ménard et al. 2010) to constrain this dependence and potentially even the extinction law of the dust in sub-millimetre galaxies.

For consistency, we also calculate models where the dust is assumed to be distributed according to an exponential profile with different scale lengths $h_R = 5 - 40 \text{ kpc}$ instead of an NFW-like dust halo. The factor c_d becomes a function of angular scale then, and so do the weights for the optimally weighted correlation function. The overall amplitude of these dust models is fixed by the measured, integrated value of c_d at small scales (see Fig. 2). The best-fit mass for such models is smaller by a factor 2–3 than the best-fit mass for the model with an NFW-like dust halo – the larger the scale length the smaller the discrepancy. However, the reduced χ^2 of these model fits to the data, $\chi^2/\text{dof} = 2-5$, is considerably larger than the fiducial $\chi^2/\text{dof} = 1.5$ of the model with an NFW-like dust component – again with the largest dust scale length (40 kpc) yielding the smallest χ^2/dof . This indicates that the dust is indeed very widely distributed, and our measurements favour the fiducial model where “dust follows mass”. It should be stressed that we do not interpret the results in such a way that these sub-millimetre galaxies have a smooth NFW-like dust halo or exponential dust disks with very large scale-lengths of $h_R \gtrsim 40 \text{ kpc}$. It is, however, possible that some additional, widely extended dust component – similar to what is found in Ménard et al. (2010) – is responsible for the effect seen here.

Another consequence of the limited signal-to-noise ratio

⁶ It should be noted that the estimate from IR abundance matching is associated with a number of systematic errors that are not present in the magnification measurement.

is that we cannot fit a multi-parameter model to the data points in Fig.3. For this reason we concentrate on small angular scales, where a single halo can be assumed to dominate (1-halo term). The contributions from other halos (2-halo term) only become important at larger angular scales and can be neglected here for simplicity. Further assuming a mass-concentration relation (Prada et al. 2012) for the NFW halo leaves us with just one parameter to fit, the average mass M_{200} . We check the influence of our choice of a particular mass-concentration relation by also implementing the relation by Muñoz-Cuarteras et al. (2011) and find a negligible difference in the best-fit mass of $\Delta \log_{10} [M_{200}/M_{\odot}] \approx 0.03$. Again, the interpretation of a measurement from a more powerful, larger-area survey could easily be extended to constrain the halo-occupation distributions, satellite fractions, and concentration parameters directly.

We also assume that all sub-millimetre galaxies are central galaxies to their halos. There are some indications in the literature from clustering studies that a fair fraction of the galaxies in such a sub-millimetre sample are in fact satellites ($\sim 25\%$ for our lens sample; see Cooray et al. 2010). In the regime probed here the magnification excess, δ_{μ} , is fairly linear in the mass. Thus, assuming a worst-case scenario, where no mass would be associated with 25% of our lenses, this would lead to an underestimate of the halo mass of the remaining 75% central galaxies of $\Delta \log_{10} [M_{200}/M_{\odot}] \approx 0.1$. This is similar to the statistical error of our measurement so that we decided not to correct for this directly here, especially because the real effect is certainly smaller than this worst-case scenario.

7 SUMMARY AND OUTLOOK

In this paper we show how to use the magnification effect of WL to measure the average mass of sub-millimetre galaxies. Using sub-millimetre galaxies as the lenses and Lyman-break galaxies as the sources we find a mass of $\log_{10} [M_{200}/M_{\odot}] = 13.17^{+0.05}_{-0.08}$ (stat.) for the halos hosting the sub-millimetre galaxies. The presence of significant amounts of extinction by dust in the lenses complicates this measurement. However, accounting for the dust allows us to simultaneously constrain the dust mass fraction of the lenses to $M_{\text{dust}}/M_{200} \approx 6 \times 10^{-5}$.

With deep, large-area, imaging surveys (DES, LSST, Euclid) on the horizon, WL-magnification methods will gain additional importance. The higher the redshifts of the objects under study, the fewer the techniques that can provide a reliable mass measurement. As we have shown in this paper, magnification can provide such mass estimates for high redshift objects. Follow-up observations of the optical surveys mentioned above with sub-millimetre telescopes will provide very large samples of high- z star-forming galaxies. Refined magnification measurements of the kind presented here, alongside with clustering measurements and other techniques, will yield unprecedented insights into the physical processes of star-formation in the first half of the Universe.

Future measurements with better statistics will enable the lensing and extinction effects to be separated. Additional redshift information for the sub-millimetre galaxies will lead to more accurate mass estimates. By splitting the

sub-millimetre galaxy sample in brightness it will be possible to directly study the relationship between mass and star-formation rate.

This study shows that extinction can not be neglected in magnification studies. The studies by Hildebrandt et al. (2009b) and Morrison et al. (2012) show excessive anti-correlations when very faint sources are used. Also the amplitudes of the angular correlation function presented there turn over from positive to negative at brighter source magnitudes than expected from magnification alone. This hints at extinction playing a role. The framework outlined here can explain this effect, and we strongly suggest future magnification studies to account for extinction to avoid a systematic bias.

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Author Contributions:

H.H. led the analysis and wrote the draft version of the paper. L.v.W. and D.S. contributed significantly in the development

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